



International Journal of Engineering Research and Science & Technology

www.ijerst.org

ISSN : 2319-5991

Vol. 22 No. 1 (2026)



ijerst.editor@gmail.com
editor@ijerst.com

Research

A COGNITIVE OPTICAL ANOMALY RECOGNITION SYSTEM FOR RAILWAY INFRASTRUCTURE INTEGRITY MONITORING

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ABSTRACT:

Technological evolution is observed in railway track inspection methods due to the passage from traditional image processing methods to more innovative data-driven models, owing to the inflexibility of more traditional methods upon being exposed to real-world scenarios. Though its capability of handling uncertain inputs has been improved with the inclusion of fuzzy-logic principles in it, owing to its reliance on manually coded knowledge, it has become less relevant. The current paper discusses a new complete process for railway track inspection that combines the autonomous identification power of convolutional neural networks and the logical deduction power of fuzzy logic inference. This new process combines the autonomous identification power of CNNs with the logical deduction power of fuzzy logic inference.

KEYWORDS: Image Processing, Fuzzy Logic, Otsu Method, Rail Track Detection, Google API Method, Histogram Equalization.

Received: 31-01-2026

Accepted: 05-03-2026

Published: 12-03-2026

I. INTRODUCTION:

Automated railway crack detection has been implemented through sensor-based monitoring and image processing to detect surface and structural cracks in railway tracks [1]. Short-range data transmission has been implemented through Arduino-based visible light communication to ensure interference-free data transmission [2], while optical wireless communication through Li-Fi technology has been implemented to support efficient image transmission in monitoring systems [3]. Internal defect detection has also been implemented through infrared thermal imaging and cooling pre-treatment to improve crack detection accuracy [4]. These implementations together address the challenges of manual inspection by allowing continuous monitoring and improved safety in large railway networks.

Advanced computational models have been developed and implemented to improve the intelligence and decision-making capabilities of systems in automated inspection and control systems. Multimodal image fusion techniques based on discrete wavelet transform and Otsu's thresholding technique have been developed and implemented to improve the representation of features and clarity of information [5]. Intelligent control systems have been developed and implemented based on fuzzy logic with emergency override functions to provide real-time adaptability in dynamic situations [6], while machine learning-based classification models have been developed and implemented for automated analysis of complex image information with improved accuracy [7]. Reliability and risk assessment have also been improved by the implementation of fuzzy logic-based failure mode and effects analysis, which

significantly reduces the chances of critical system failures [8].

Recent studies have incorporated anomaly detection through the analysis and application of sophisticated image segmentation algorithms appropriate for industrial inspection applications [9]. Machine learning and hyperspectral image processing have also been incorporated for the precise identification of mineral composition through spectral analysis [10], while autonomous navigation has been incorporated through Fibonacci path planning algorithms for optimal and collision-free motion in indoor robotic platforms [11]. Such approaches illustrate the increasing use of intelligent image analysis and optimization algorithms in automated inspection, material identification, and autonomous control.

II. LITERATURE SURVEY

Solutions proposed for the automated inspection of railway networks vary widely, ranging from simple vision-based solutions to highly complex ones based on artificial intelligence[1][7]. Although advanced imaging and intelligent algorithms have helped improve the accuracy of defect detection in uncertain and complex environments, there are a number of challenges that remain. [8]Fuzzy classifiers have been proposed to address the issue of ambiguity during defect detection, but most of the existing solutions have been designed and tested in a controlled environment. This makes it difficult to implement them in a large national railway network. Although high-resolution cameras can help improve the accuracy of defect detection, there are a number of challenges associated with their use.

Conventional image analysis methods are mainly useful for the detection of[1] surface-level defects, but they are not capable of measuring the severity or depth of defects. Stereo vision-based image analysis provides better functionality for measuring depth and analysing the severity of defects. But the performance of stereo vision systems is very sensitive to noise, vibrations, and environmental factors, which affects their reliability in real-world railway environments. Thermal and temperature-based

analysis techniques have proved their effectiveness in detecting subsurface defects in laboratory settings. But their performance is not satisfactory in real-world environments due to changes in ambient temperature, lighting, and surrounding conditions. In addition, most of the existing literature is based on isolated defect types, such as cracks and ballast, instead of a comprehensive analysis of track condition.

[6] Fuzzy inference systems have the natural ability to cope with uncertainty and imprecision, making them suitable for railway inspection tasks. When coupled with effective data transmission techniques, fuzzy inference systems can be used for intelligent decision-making. However, the problems related to signal connectivity, contrast variations, and inconsistent environmental conditions are still hampering their performance. The present structure of fuzzy systems is only capable of handling one inspection task and lacks flexibility to handle multiple working conditions simultaneously.

The weaknesses identified in the current methods underscore the importance of an integrated inspection system that leverages the best of different methods. A hybrid system that integrates sophisticated image acquisition, optimized image transmission, and smart inference processing can counter the weaknesses of different methods. An integrated system can offer assured accuracy, valid defect analysis, and flexibility to accommodate changes in operating conditions. By considering surface and subsurface defects and taking into account uncertainties and changes in operating conditions, an integrated system offers a more realistic and effective approach to overcome the difficulties in modern railway inspection.

III. MODULES

A. RELATED APPROACH

In this paper, a deep learning solution using a CNN structure is proposed to improve the accuracy and robustness of railway track diagnosis. Unlike conventional approaches, which rely heavily on manually designed features, the proposed system uses the CNN structure to automatically learn distinctive

features from images taken using the ESP32-CAM module. The proposed system is capable of detecting various railway track anomalies, such as surface cracks, welding defects, track misalignment, and ballast irregularities. The proposed system is also capable of performing comprehensive and scalable railway track analysis because it combines the detection of various types of anomalies in a single model.

However, despite the benefits offered by CNN-based models, there are several issues that arise during practical implementation. The creation of effective deep learning models requires a significant amount of labeled training data, which is especially true for rare or regional track defects. Insufficient diversity in the dataset may cause overfitting and result in poor generalization performance. Additionally, the CNN model usually has high computational complexity and training time, making it impractical for implementation on edge devices. The model performance can also be affected by unseen environmental factors such as low light, rain, dust, or motion blur.

To tackle these problems, the proposed framework focuses on efficient model design, optimized inference paths, and strategic data transmission approaches that are more suitable for edge deployment. Through a careful trade-off between model accuracy, computational complexity, and system scalability, the proposed solution is expected to provide a viable solution for intelligent railway track monitoring. The combination of deep learning with intelligent decision support systems provides a reliable means of detection, which helps to improve railway safety and minimize maintenance costs.

B. PROPOSED SYSTEM

The proposed system is intended to offer a reliable and intelligent solution for railway track maintenance through automated monitoring and analysis. The main purpose of the proposed system is to improve railway safety by ensuring the early detection and accurate analysis of structural defects. The proposed system architecture includes a Convolutional Neural Network (CNN) that analyses images captured using ESP32-CAM modules. The

cameras are continuously capturing visual information of the railway tracks, which helps the system detect surface and structural defects such as cracks, weld defects, track displacement, and ballast irregularities with high accuracy.

The output produced by the CNN is then passed on to a fuzzy logic-based decision-making module. The fuzzy inference system assesses the severity level of the identified anomalies based on various parameters like size, shape, position, and confidence level of the identified anomaly as provided by the CNN. In contrast to the traditional method of thresholding, the fuzzy logic module is very effective in handling uncertainty and imprecision, which makes it possible to have a more detailed assessment of the track conditions. The integration of deep learning and fuzzy logic makes it possible for the system to not only detect anomalies but also prioritize their maintenance based on the level of severity.

One of the key strengths of the proposed hybrid model is its ability to perform well in different environmental settings. The model has been designed to work well in different weather conditions, such as varying lighting conditions, temperature, and atmosphere. Since the decision-making process in the model is based on patterns and fuzzy logic, it will be able to perform well even if the environmental conditions are not consistent.

Moreover, the proposed model provides high scalability and integration capabilities within the existing railway infrastructure. The small size of ESP32-CAM modules and the modular software design enable the system to be expanded over vast railway networks with less modification. The system can be implemented on mobile inspection vehicles or stationary monitoring stations, which will enable perpetual observation without halting the normal train services. Through enhanced detection accuracy, reduced human interaction, and smart maintenance planning, the proposed system will promote safe, efficient, and reliable railway transport.

IV. SYSTEM DESIGN

SYSTEM ARCHITECTURE

Below diagram depicts the whole system architecture.

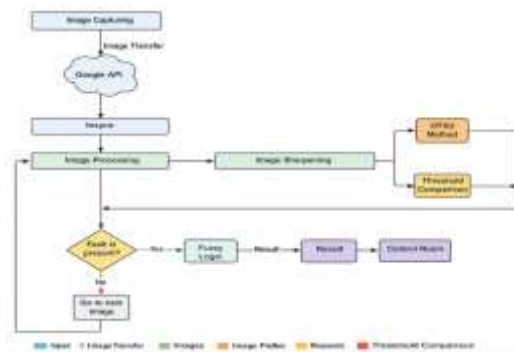


Fig 1. Methodology followed for proposed model

The fig 1 describes an image analysis process that is step by step and aims to automatically detect any defects. The process begins with the acquisition of images, which are then uploaded to a cloud-based system using an application interface for synchronization. The images are then processed using enhancement and sharpening methods to highlight key features. After image enhancement, statistical thresholding methods are used to distinguish normal areas from potential defect areas. The system then analyzes the result to see whether there is a defect, and images without defects are removed while those with defects are analyzed by using fuzzy logic to improve the detection of defects. Finally, the results of the analysis are produced and transmitted to the control room for monitoring and necessary actions.

V. SYSTEM IMPLEMENTATION MODULES

1. Image Acquisition Subsystem

Objective:

To enable precise visual assessment of railway infrastructure through continuous image acquisition.

Description:

A mobile robotic platform integrated with an ESP32-CAM captures track images during routine movement along railway lines. Image capture is scheduled at regular time gaps, while adaptive exposure and brightness controls compensate for changes in natural lighting, ensuring uniform visual output throughout the inspection process.

2. Data Management and Synchronization

Objective:

To manage inspection data in an organized, secure, and synchronized manner.

Description:

The cloud storage system is designed to organize incoming images into systematic directories with timestamps corresponding to location metadata. This facilitates easy data access for real-time inspection and historical analysis of railway track conditions. Data synchronization tools are employed to maintain consistency among devices, and data security measures are implemented to prevent misuse of sensitive inspection data.

3. Image Conditioning and Visual Enhancement

Objective:

The objective of this stage is to achieve better visual clarity by removing unwanted distortions, thereby allowing for accurate identification of track defects.

Description:

Raw images obtained from the inspection system are first optimized using dimensional scaling and intensity standardization to enhance processing speed. Colour components are converted to luminance for easier analysis. Advanced noise removal algorithms are then applied to remove artifacts introduced by dust, vibration, and outdoor lighting conditions. Edge enhancement operators are used to highlight minute surface irregularities, and contrast redistribution algorithms are applied to make minute cracks and discontinuities more visible in complex visual scenes.

4. Targeted Track Area Extraction (ROI Identification)

Objective:

The objective of this stage is to accurately isolate rail-specific areas for focused defect analysis.

Description:

The system uses spatial separation techniques to separate the rail area from non-relevant background areas such as sleepers, gravel, and vegetation. Adaptive decision algorithms are used to identify rail boundaries, which are then

refined using structural refinement algorithms to enhance region identification. Geometric consistency and surface texture properties are analysed to detect irregular formations, thereby ensuring that analysis is focused on areas with a higher likelihood of structural irregularities.

5. Track Defect Identification and Categorization

Objective:

To accurately identify and distinguish various types of structural defects occurring on railway tracks.

Description:

The identified rail area images are analysed for structural defects and imperfections on the surface of the tracks using sophisticated recognition techniques. Various visual characteristics, such as surface texture, shape, and size irregularities, are measured and converted into meaningful feature vectors. These feature vectors are further analyzed by trained classification models, which identify each type of defect occurring on the tracks.

6. Severity Estimation Using Fuzzy Reasoning

Objective:

To accurately assess the severity of the identified defects for efficient maintenance planning.

Description:

A fuzzy rule-based assessment system is used to estimate the severity of the defects by combining multiple uncertain factors, including the severity of the defect, the level of structural damage, and the reliability of the classification results. Rather than using fixed numerical values, the system uses linguistic terms (low, moderate, high, extreme) to assess these inputs.

7. Intelligent Autonomous Motion and Control System

Objective:

To provide reliable and safe autonomous self-navigation of the inspection robot on railway tracks.

Description:

The robotic system uses proximity sensing technologies to ensure precise tracking alignment during robot movement. Positioning information obtained from satellite navigation and wireless communication modules allows

real-time tracking of the robot's location and path recording. Real-time dynamic obstacle detection allows the robot to instantly change its speed or direction to avoid collisions and achieve continuous inspection without human intervention.

8. Insight Delivery and Visualization Platform

Objective:

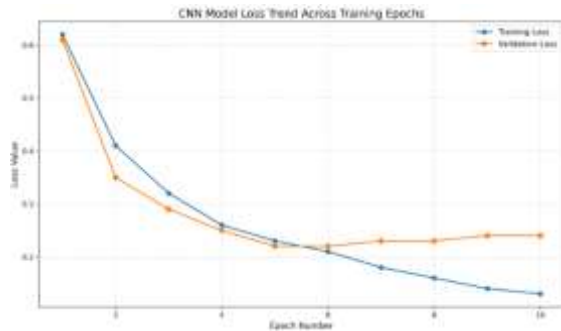
To provide operators and maintenance planners with actionable intelligence from inspection results.

Description:

Inspection results are presented in an interactive visual space that includes spatial mapping, severity-level indicators, and location-specific fault indicators. Automated alerts are generated for critical issues that demand immediate attention, while inspection history records allow long-term performance analysis and maintenance prediction. This system enables railway management to take immediate and strategic actions based on data-driven intelligence.

VI . RESULTS AND DISCUSSION

The graph shows the progression of error values generated by a convolutional neural network as the training process continues with each learning cycle. At the initial stage, elevated error levels indicate that the model has not yet learned the underlying data structure. With continued training, the error measured on the training dataset steadily reduces, reflecting effective optimization of network parameters.. The error value for unseen data reduces at first and then stabilizes with a slight rise, indicating that the network has achieved optimal learning equilibrium. The implication is that further learning will result in little improvement in the prediction capability, while the proximity of the two curves indicates stable and sound generalization.



VII. CONCLUSION AND FUTURE WORK

The need for modernization of railway infrastructure requires a shift from manual inspection to continuous automated condition monitoring, which is achieved by integrating Digital Image Processing (DIP) with Fuzzy Logic Control (FLC). In this combined system, image processing is the sensing component that uses high-speed cameras to record continuous footage of rail, fasteners, and sleepers. Prior to processing, the raw data is purified using pre-processing algorithms to eliminate environmental noise such as shadows or oil, thereby ensuring that the rail is distinguishable from the background. Sophisticated feature extraction algorithms, including edge detection, are then employed to search the geometry for defects. This optical component enables the system to quickly detect irregularities in the structure, from surface cracks to gauge expansion, at high speeds that would be impractical for human inspectors to manually cover.

The fusion of advanced image processing techniques with fuzzy logic reasoning is a paradigm shift in railway infrastructure maintenance, propelling the sector from a reactive repair mindset to an intelligent and proactive monitoring approach. The first step in this technology is the optical acquisition layer, where high-speed cameras and sensors record high-resolution images of the rail infrastructure, including the rail head, fasteners, and sleepers. However, since the images are prone to environmental "noise" in the form of changing sunlight, shadows, or debris, the system uses advanced pre-processing algorithms. Gaussian smoothing and histogram equalization are used first to normalize the contrast and eliminate

visual noise or static. Next, the system uses image segmentation techniques, including Otsu's thresholding algorithm, to separate the rail infrastructure from the background. This enables accurate feature extraction, where edge detection operators (such as the Canny or Sobel operators) encode the geometry of the rail infrastructure, highlighting potential defects such as surface cracks, corrugations, or missing bolts.

After the visual data is harvested, the system needs to calculate the level of severity for the detected anomalies, which is better handled by Fuzzy Logic Control (FLC) than by binary computing. In binary computing, a flaw is either "present" or "absent," but in rail safety, the level of the flaw is of utmost importance. The data harvested from the images, such as the size and orientation of a crack, is used as input for the fuzzy inference system. By a process called fuzzification, these precise numerical values are transformed into linguistic variables (such as "Minor," "Moderate," and "Severe") by membership functions. The system then processes these variables by a knowledge base of "IF-THEN" rules developed from human engineering knowledge (such as "IF the width of the crack is Wide AND its location is Rail Head, THEN Urgency is High"). This simulates human reasoning, enabling the system to process the uncertainties and ambiguities present in actual data.

The final step, defuzzification, is where the fuzzy results are converted back into a hard, usable number, such as a "Safety Index" or a maintenance priority level. This combination of computer vision and computational intelligence has greatly minimized the occurrence of false alarms, which is a common problem with purely visual systems, as it has the capability to differentiate between a harmless surface scratch and a structural fracture that could be a danger to derailment. With the ability to properly diagnose the stages of wear and tear, train operators can begin to utilize predictive maintenance techniques, performing maintenance during off-peak hours as opposed to having to make emergency shutdowns.

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